

Dynamic Modeling for Evaluation of Solar Collector Performance

C. L. Hamilton
TDA Planning Office

A dynamic model program designed to aid in the understanding of solar collector behavior over the full range of operating conditions has been constructed and tested in the evaluation of a conceptual collector design.

I. Introduction

Dynamic modeling is being developed to provide a tool for systematic analysis of performance characteristics in energy systems where time-dependent behavior is important. It is intended that the technique be applicable to many levels of detail in analysis, from rough examination of system behavior in response to general specifications on subsystem performances to very detailed analysis of the effect exerted on a component's transient and integrated performance by its various characteristics. References 1 and 2 have discussed modeling of solar energy systems in terms of gross subsystem specifications. This paper reports work on simulating the performance of solar collectors by themselves, to allow more detailed understanding of one important system component. Construction of a model and its embodiment in a computer program were carried out using now standard procedures. The program was used to estimate the behavior to be expected from a conceptual collector design and then to check its variance with collector orientation.

II. Construction of Model and Program

The collector performance model is strictly analogous to the one embodied in program SUN (Ref. 1), except that it represents only one physical component. Therefore the program COLTEST, in which it is embodied, carries a single computational module. That computational module contains the same interfaces with environment and other components as the Solar Collector Module in SUN does (Fig. 1). Collector performance is determined by the intensity and angle of solar radiation, by ambient temperature, and by the temperature of fluid entering it from storage or a conversion device. Energy output from the collector is described by the rate of heat extraction from it and the temperature at which that heat is removed.

This particular program (named COLTEST for *Collector Test*) was intended to aid in understanding what happens to the energy gathered by a collector throughout a day's operation. For that reason it was set up to accept

exogenous inputs and record output at closely spaced intervals, simulating performance for a period of one day. Several derived values were produced, tabulating the fate of incoming radiation under the various modes of operation encountered; these are combined in the performance curve shown in Fig. 2. The analysis was done assuming the same collector operating strategy as employed in the system test analyses using programs SUN (Ref. 1) and SENSMOD2 (Ref. 2)—namely that the heat transfer fluid in the collector would be kept static until it had attained a minimum temperature. Once that minimum temperature was reached, the fluid flow rate would be regulated to keep the outlet temperature within a range of 10–15°C above the minimum. At the end of the day, when the temperature out of the collector dropped below the turn-on level, flow was again stopped.

At the end of each fifteen minutes of simulated operation, several rates were output. These were expressed as the averages experienced over that period (all in kW/m² of collector surface) and consisted of the radiation rate incident on the collector's front face, the radiation rate reaching and absorbed by the absorber surface, the rate at which absorbed energy is retained as sensible heat bringing the collector up to operating temperature, the heat loss rate, and the rate at which energy at or above the minimum operating temperature is extracted by the collector fluid. Cumulative variables recording the amount of energy funneled into each of the above categories (in kWh/m²) were also printed, allowing estimation of integrated daily collector performance.

Measured values of solar radiation, recorded as intensity incident on a horizontal surface at Deep Space Station 13, Goldstone Space Communications Complex, on June 2, 1975, provided the basis for input files to drive the model. The sun's declination and transit time for that date were used to generate files containing values for angle of incidence of sunlight on the face of collectors facing south and tilted at various angles from horizontal. These entries were recorded at fifteen minute intervals, from 00:00 to 24:45 PST; a value of 90 deg was entered for all times in which the sun was not shining on the collector face. With the angles of incidence, files containing intensities on the front surfaces of appropriately tilted collectors, varying every fifteen minutes, were calculated from the horizontal measurements. In addition to the radiation intensity and angle-of-incidence files, a third input file was compiled from fifteen-minute readings of ambient temperature at the same location on the same day. All measurements used here were made under a program that has been conducted at Goldstone Space Communications Complex (GSCC)

since June 1974, dedicated to collecting an archive of solar data calibrated to the international standard (Ref. 3).

Because COLTEST was intended to fulfill a specific purpose (tracing aspects of collector performance one day at a time) and would never contain more than one computational module, its structure could be somewhat simpler than that of the more general programs embodying system models for which a wider range of manipulation is desired. Figures 4 and 5 are the flow charts describing the program. As in program SUN, collector behavior is simulated, in DHCALC, using a variable integration interval to achieve computational stability without requiring excessive iterations through the program's calculation loop. The variable-step-size loop is imbedded in a more slowly varying loop with step size $DT = 1/4$ hr, synchronized with the interval at which new exogenous inputs are supplied. The slower loop is where the fifteen-minute average rates are computed for output and where the corresponding cumulative variables are updated. As in all of the dynamic model programs, substitution of one component for another involves replacement of limited and discrete subprogram segments. An entirely different collector characterization can be submitted for analysis by substituting subprograms COLCALC (block 1.4.3), COLCC (1.4.4), and COLUPD (1.4.5), along with appropriate initialization statements.

III. Test of the Program

COLTEST was first exercised in estimating performance characteristics for a conceptual collector design that arose while the Goldstone Energy Project was looking into solar-fired power-on-demand systems. The system under consideration required delivery of heat at 300°C or above, and was estimated to return fluid to the collector with a 50°C temperature drop. The hypothetical collector was to have a concentration ratio of 2, involving a single glass cover with 94 percent transmissivity to normal radiation. A selectively coated absorber tube of thin copper was postulated; the coating was specified to have 90 percent absorptivity and 5 percent emissivity. The collector fluid was air, and the minimum operating temperature to be maintained was 300°C. It was specified that heat loss from the collector would be predominantly radiative, and amount to about 360 W/m² at an absorber temperature of 350°C. Note that this collector description is in terms of specifications on a hypothetical piece of hardware, and the function of the dynamic model here is to translate these specifications into a measure of collector performance and to reveal the sensitivity of that performance to those specifications.

The program was run for this conceptual collector design at two tilt angles. Results from the two runs are summarized in Figs. 2 and 3. Plotted as a function of time are the fifteen-minute average rates listed above. The outer envelope represents solar radiation incident on the collector's front face, while the line below that shows the rate at which energy reaches and is absorbed by the absorber surface. The difference in the areas under the two curves represents the percentage of daily total insolation that is uncollectable owing to the optical properties of the cover material. A small slice of the absorbed energy was sacrificed in the morning hours to satisfy the assumed requirement for relatively constant output temperature that is marked Energy Lost in Warmup on the figures; its very small size reflects the low thermal capacitance inherent in a thin copper tube using air as a heat transfer fluid. Along the bottom of each figure is a band reflecting heat loss. This is a combination of radiative and conductive loss and is consistent with a well-insulated collector with the specified absorber coating properties. Subtraction of the total losses from energy absorbed gives the area in the middle of the figure,

measuring the daily total useful energy extracted. For the collector tilted at 48.5 deg, integrated collector efficiency for that day would have been 46 percent. Changing collector angle to 20 deg, which is more favorable for summer collection, increases integrated efficiency to 57 percent. In both these cases the collector functioned with an average absorber temperature very close to 325°C during the whole period of useful energy delivery. Sensitivity analyses were not carried further, owing to a shift in project emphasis.

IV. Summary

Program COLTEST was developed for the purpose of carrying out specific performance studies on solar collectors. It was used to some extent for predicting behavior based on preliminary specifications of a hypothetical collector. More recently a commercially available collector, characterized by a general and detailed heat transfer analysis, has been examined using COLTEST. A separate report on that work is forthcoming.

References

1. Hamilton, C. L., "A Dynamic Model for Analysis of Solar Energy Systems," in *The Deep Space Network Progress Report 42-27*, pp. 41-51. Jet Propulsion Laboratory, Pasadena, California, June 15, 1975.
2. Hamilton, C. L., "An Experiment in Dynamic Modeling for a Complete Solar-Powered Energy System," in *The Deep Space Network Progress Report 42-31*, pp. 137-143. Jet Propulsion Laboratory, Pasadena, California, February 15, 1976.
3. Reid, M. S., Gardner, R. A., and Parham, O. B., "The Goldstone Solar Energy Instrumentation Project: Description, Instrumentation and Preliminary Results," in *The Deep Space Network Progress Report 42-26*, pp. 133-144. Jet Propulsion Laboratory, Pasadena, California, April 15, 1975.

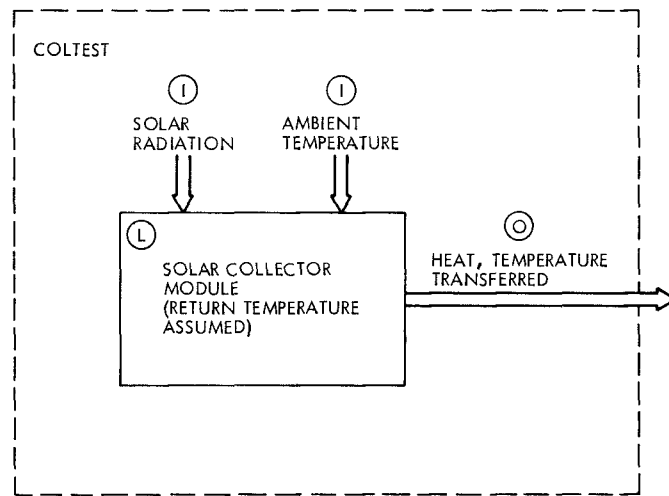


Fig. 1. Computational module and data interfaces

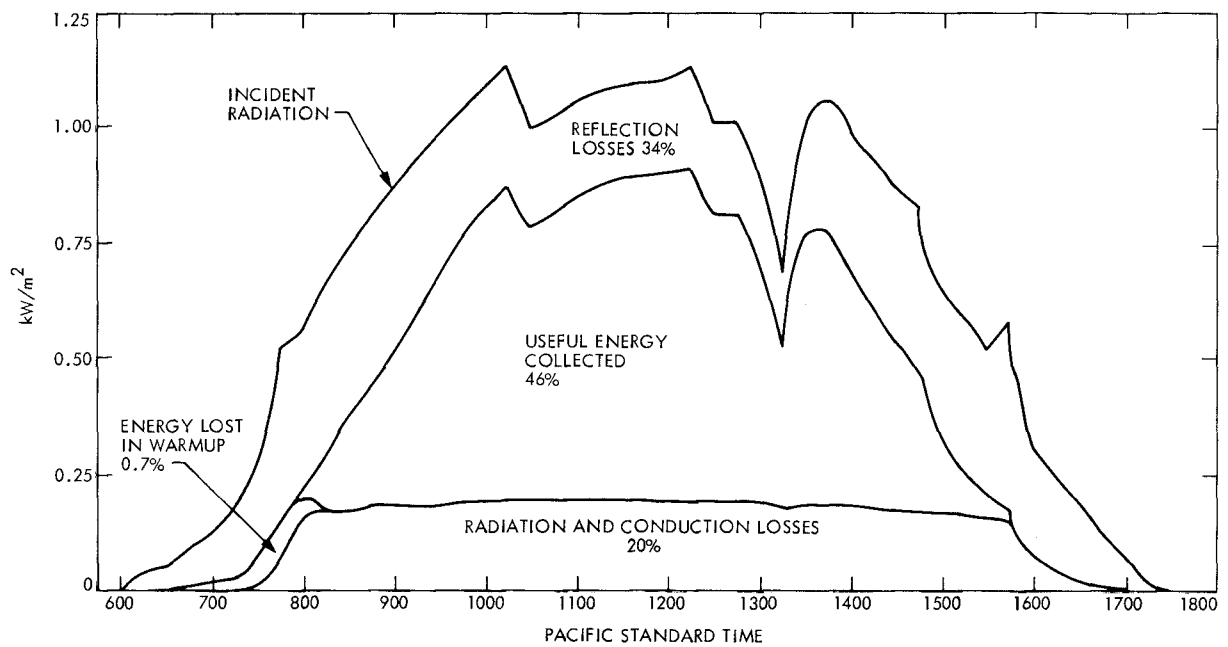


Fig. 2. Performance of collector tilted at 48.5 deg from horizontal

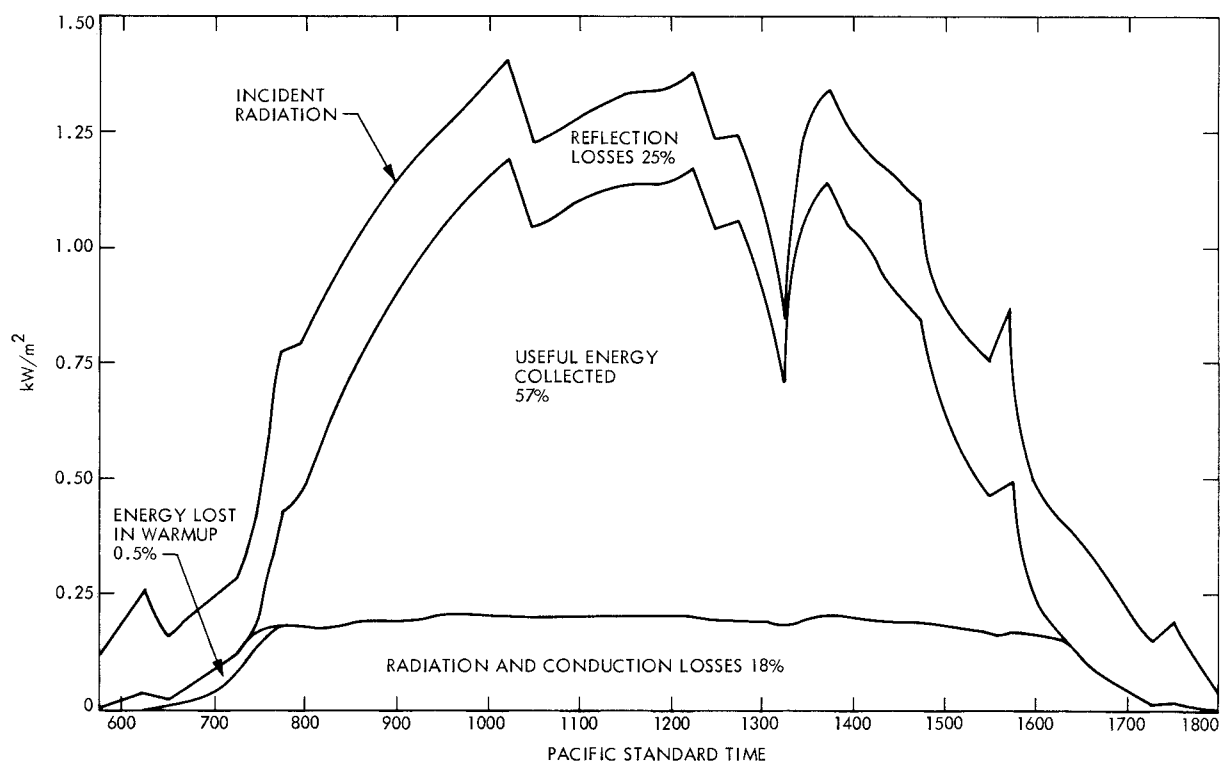


Fig. 3. Performance of collector tilted at 20 deg from horizontal

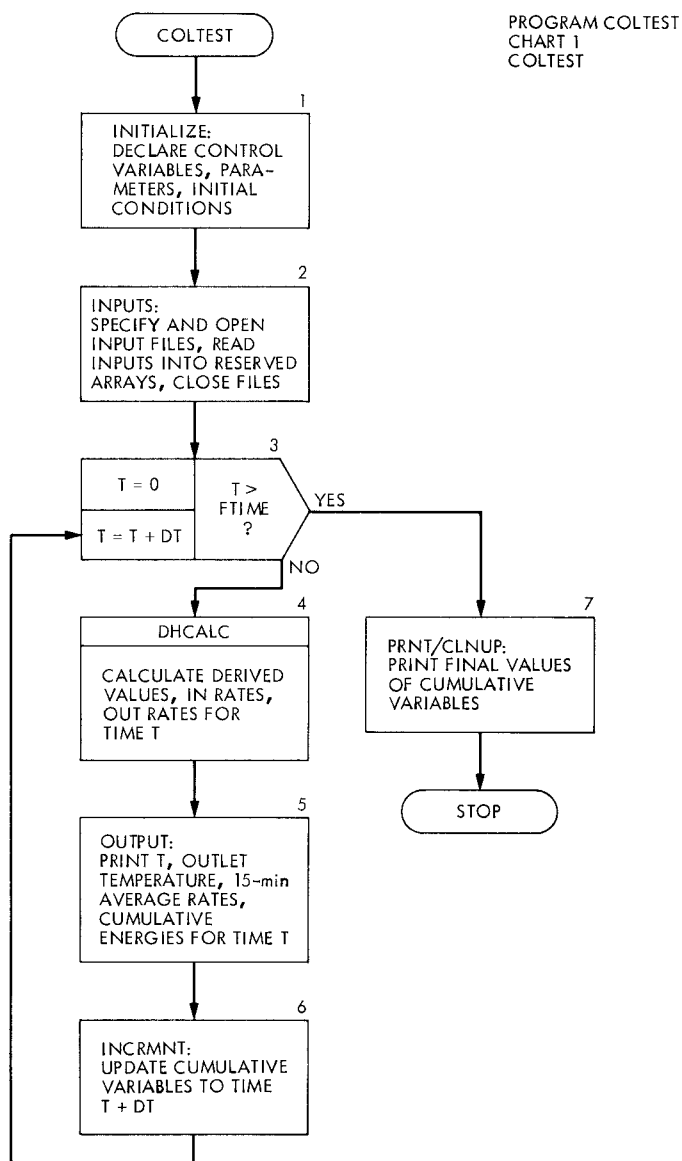


Fig. 4. Level 1 structure, Program COLTEST

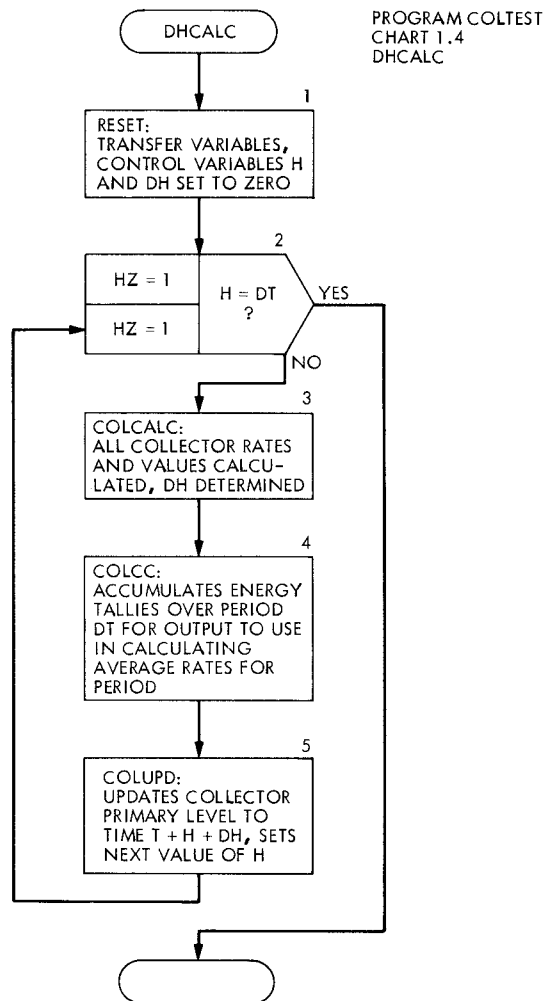


Fig. 5. Level 2 structure, Program COLTEST